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RESEARCH MEMORANDUM

SOME OPERATING EXPERIENCE AND PROBLEMS ENCOUNTERED DURING OPERATION OF A FREE-JET FACILITY

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SOME OPERATING EXPERIENCE AND PROBLEMS ENCOUNTERED DURING OPERATION OF A FREE-JET FACILITY

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SUMMARY

The initial data obtained during a free-jet investigation of a 28-inch ram-jet engine at a Mach number of 2.35 disclosed that the engine rich blowout limits occurred at considerably lower fuel-air ratios than those observed during direct-connect testing by the manufacturer in his facility. Installation of a shadowgraph and high-response pressure instrumentation revealed random pressure pulsations in the flow at the diffuser inlet. Removal of these pulsations by placing a fine, spherical screen at the bellmouth inlet of the supersonic nozzle increased the engine rich blowout fuel-air ratio about 10 percent and the peak diffuser pressure recovery 2 points. The flow pulsations had no discernible effect on the supercritical mass-flow ratio or the engine combustion efficiency. Installation of a jet diffuser at the exit of the supersonic nozzle reduced the facility pressure ratio necessary to obtain flow simulation by 25 percent at a Mach number of 2.70. However, the jet diffuser markedly decreased the range of subcritical engine operation that could be obtained.

INTRODUCTION

The performance of ram-jet engines at high Mach numbers may be obtained by flight, supersonic wind tunnel, direct-connect, and free-jet testing techniques. Of these, the free-jet method is the simplest and most economical technique that permits an accurate simulation of internal-flow conditions that exist in flight.

Several investigations of the design and performance of free-jet facilities have been reported previously. Small-scale model investigations of the design of jet diffusers, the optimum free-jet nozzle size, and the positioning of the diffuser inlet with respect to the supersonic nozzle are reported in references 1 and 2. Some of the special problems associated with asymmetric free-jet facilities are considered in references 2 and 3. Brief investigations of two free-jet facilities large enough for 48-inch and 20-inch ram-jet engines are reported in references 3 and 4, respectively.

Because the information published on the free-jet testing technique is rather sparse, particularly for full-scale tests, any additional information that might aid in the design or operation of such a free-jet facility would be quite useful. Accordingly, this report presents the operating experience and problems encountered with a free-jet facility designed to simulate the internal-flow conditions of a 28-inch ram-jet engine over a range of angles of attack from +7° to -7° at Mach numbers of 1.92, 2.35, 2.50, and 2.70. This report concerns mainly a facility flow pulsation encountered during the performance evaluation of the ram-jet engine: how it was eliminated and what its effect was on the engine performance and operational characteristics. The starting and operating facility pressure ratios required for proper flow simulation are also presented. A limited amount of data are shown to indicate the degree of subcritical operation permitted before the inlet flow simulation broke down.

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APPARATUS AND PROCEDURE

Facility Description

A schematic diagram showing the supersonic nozzle and ram-jet engine installed in an altitude test chamber is presented in figure 1. Four different supersonic nozzles were used during the investigation. The 2.35, 2.50, and 2.70 Mach number nozzles had exit diameters of about 32.8 inches, and their exits were located 5 inches upstream of the engine cowl lip. The 1.92 Mach number nozzle had an exit diameter of about 27.5 inches, and its exit was also located 5 inches upstream of the engine cowl lip. The cowl lip diameter of the engine was 17.8 inches.

The inlet air is brought to the desired condition by passing through compressors, driers, and heaters (not shown). This air is required to negotiate two 90° turns (fig. 1) with the aid of straightening vanes before it passes into the plenum chamber where the supersonic nozzle is located. The pressure in the test chamber, which is separated from the plenum chamber by a bulkhead (fig. 1), is reduced so that the flow is accelerated through the supersonic nozzle to the desired Mach number at the engine inlet. Part of the air enters the engine, and the remainder is bypassed around the engine into the test chamber. In some cases, a jet diffuser was attached to the exit of the supersonic nozzle. The length of the diffuser is about 30 inches, and its inlet and outlet diameters are 32.8 and 43.4 inches, respectively. The supersonic nozzle was pivoted about an axis on the engine centerline near the nozzle exit in order to simulate angles of attack from -7° to +7°.

Facility Modifications

During the investigation several modifications were made to the facility to eliminate pulsations in the flow entering the engine. These modifications included: (1) 16 angle irons placed in the diffuser section ahead of the plenum chamber (fig. 1), (2) a 30-mesh spherical screen designed for a 3q pressure drop attached to the bellmouth of the supersonic nozzle (figs. 1 and 2), and (3) a 30-mesh screen placed at the inlet of the plenum chamber (figs. 1 and 2).

Instrumentation

The instrumentation consisted of total-pressure probes at the bellmouth inlet of the supersonic nozzle, the engine diffuser outlet, and the engine exhaust-nozzle throat, and static-pressure taps along the diverging section of the supersonic nozzle, at the engine cowl lip, and in the rear of the test chamber. The inlet air temperature was measured by thermocouples located at the supersonic nozzle inlet. In addition, high-response pressure instrumentation (relatively flat frequency response out to 200 cps) was used to measure transient static and total pressures at the inlet and outlet of the supersonic nozzle.

A shadowgraph was installed in order to view the inlet shock patterns and, in conjunction with a high-speed movie camera, to obtain a permanent record of these patterns. The area that could be observed by means of the shadowgraph is shown in the schematic diagram in figure 3. The speed at which the camera was operated was generally about 2500 frames per second.

RESULTS AND DISCUSSION

Correction and Effect of Facility Flow Pulsations

Facility flow pulsations. - Because the supersonic nozzles used for the investigation were calibrated by the engine manufacturer, further nozzle calibrations at the Lewis laboratory were considered unnecessary. Thus, the investigation began immediately with the engine performance evaluation.

An analysis of engine data obtained at a Mach number of 2.35 showed that the rich blowout limits occurred at considerably lower fuel-air ratios than those observed during direct-connect tests by the manufacturer in his facility. Measurement of the diffuser pressure recovery at blowout also indicated that the engine blowout limits were occurring before the inlet diffuser reached peak pressure recovery. Further study of the data caused considerable doubt as to whether the supersonic nozzle was providing the necessary flow conditions.

Consequently, the high-response pressure instrumentation was installed in the supersonic nozzle along with a shadowgraph to observe the engine-inlet flow. The transient pressure measurements, typical traces which are schematically presented in figure 4, showed random pulsations. These pulsations, at least the ones of sizable magnitude, were only found near the wall at the exit of the supersonic nozzle and not in that portion of the flow which was to enter the engine. At this point the magnitude of the pulsations reached as high as 10 percent of the free-stream total pressure. High-speed motion pictures indicated a rapid random movement of the conical shock originating from the tip of the inlet spike. Two motion-picture frames showing the maximum movement of the conical shock are presented in figure 5. The shock angle varied from 37.0° to 39.8°, which corresponds to a change in Mach number from about 2.5 to 2.2.

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On the basis of these observations certain conclusions can be reached as to the probable flow mechanism associated with the shock oscillations. Inasmuch as the pressure pulsations were observed only near the wall of the supersonic nozzle exit and not in that portion of the nozzle flow which passed through the engine, it is probable that there was a variation in effective nozzle-exit area that accompanied the boundary pressure pulsations. Such an area variation would, of course, introduce corresponding Mach number oscillations that would explain the observed oblique-shock movement. Thus, the inlet was apparently operating in a flow field where the total pressure was constant, but the Mach number was oscillating in a random manner, between about 2.2 and 2.5.

<u>Attempted modifications to eliminate pulsations</u>. - The approach taken to eliminate the flow pulsations was to smooth out any flow distortions arising because of the two 90° bends in the inlet air duct ahead of the plenum chamber (fig. 1) or flow separation around the lip of the bellmouth inlet to the supersonic nozzle. Consequently, three modifications were employed and are listed chronologically: (1) angle irons ahead of the plenum chamber, (2) screens at the bellmouth inlet of the supersonic nozzle, and (3) screens at the plenum-chamber inlet.

The angle irons produced no noticeable change in the movement of the conical shock. The screens at the bellmouth inlet of the supersonic nozzle proved to be quite successful inasmuch as the high-speed motion pictures indicated that the conical shock was nearly stationary. Thus, the flow was deemed satisfactory. Since the velocity contours of the flow entering a bellmouth are spherical, the bellmouth screen was similarly shaped so that pressure losses produced by the screen would be uniform.

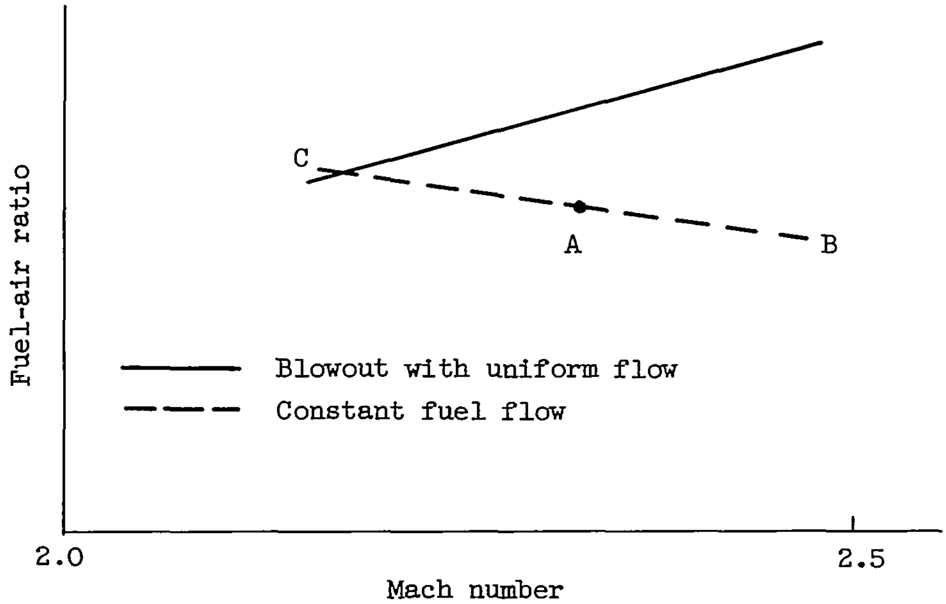
The third modification, the screen placed at the plenum-chamber inlet, was installed before the results of the spherical bellmouth screen were fully known. The plenum-chamber-inlet screen did not appreciably improve the flow uniformity already obtained with the bellmouth screen but was allowed to remain.

3967 Effect of flow pulsations on ram-jet-engine performance. - Comparison of the engine performance and operational characteristics before and after the removal of the flow pulsations revealed a significant effect of the pulsations on the engine rich blowout limits and peak diffuser pressure recovery. These changes are illustrated in figures 6 and 7 where the diffuser pressure recovery characteristics and the engine rich blowout limits for pulsating and uniform flow are presented. Elimination of the flow pulsations resulted in an increase in the diffuser peak pressure recovery of 2 points, but had no discernible effect on the diffuser supercritical mass-flow ratio (fig. 6) nor on the engine combustion efficiency (not shown).

As previously stated, the instantaneous Mach numbers during the flow pulsations varied from about 2.2 to 2.5. Consequently, the instantaneous diffuser recovery would vary between the values existing at Mach numbers of 2.2 and 2.5. However, the relatively slow responding manometer tubes would indicate a recovery somewhere between the two extremes. Such a value would not necessarily be representative of the pressure recovery at a constant value of the average Mach number.

The data presented in figure 7 indicate that the removal of the flow pulsations increased the rich blowout fuel-air ratio of the engine about 10 percent at all angles of attack. An analysis that gives a satisfactory explanation of the effect of flow pulsations on the engine rich blowout limits is possible by considering the mechanism by which blowout occurs and the effect of the Mach number variation on the engine airflow. It is important to remember that the inlet flow pulsations were random and very rapid and, therefore, the measured airflow as indicated by figure 6 was only some mean value. It has been observed (unpublished data) that the rich blowout at a Mach number of 2.35 was a result of the inlet diffuser encountering buzz (pulsation of the diffuser normal shock during subcritical operation). Consequently, whenever the inlet diffuser operating point proceeds far enough into the subcritical regime to produce diffuser buzz, the combustor is likely to blow out.

Because the Mach number oscillations were so rapid, the fuel control had insufficient time to adjust for the Mach number and, hence, engine airflow oscillations. Therefore, the fuel-air ratio was also varying rapidly inversely with the Mach number. The following sketch shows qualitatively the manner in which the fuel-air ratio would vary during a typical Mach number oscillation as compared to the fuel-air ratio required to drive the diffuser into buzz when operating with uniform flow over a comparable range of Mach numbers.



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In explanation of the preceding diagram, it is first assumed that the engine fuel-air ratio is stabilized at a point below the value required to cause engine blowout, point A. Imposing rapid oscillations in Mach number above and below the value at point A would then result in similar oscillations in fuel-air ratio along the line B-C. When this oscillation becomes of sufficient magnitude, the fuel-air ratio will move to point C, where it is sufficiently high to drive the inlet diffuser into buzz. Thus, the average or apparent fuel-air ratio resulting in blowout at a given average Mach number will be less with oscillating Mach number conditions than with uniform flow.

The preceding discussion, besides offering an explanation of the data shown in figure 7, gives a general description of the effect that gusts might have on flight engine operation. The previous example of how flow oscillations had a pronounced effect on peak pressure recovery and blowout limits clearly illustrates the importance of ensuring steady flow when operating a ram jet in a free-jet facility.

Facility Flow Simulation Characteristics

In the facility arrangements discussed in references 3 and 4, a jet diffuser was placed downstream of the engine inlet in order to provide a means of reducing the over-all facility pressure ratio required

to establish flow simulation. However, this method, although efficient in this respect, limits the degree of subcritical diffuser operation that is possible while still maintaining flow simulation. This, of course, only becomes a serious problem when the engine to be investigated operates partially or wholly in the subcritical regime, which was the case for the 28-inch ram-jet engine discussed herein. For the investigation of this engine, a shroud or jet-diffuser arrangement (fig. 1) more adaptable to angle-of-attack operation than the arrangements of
3967 references 3 and 4 was used. The jet diffuser was attached to the supersonic nozzle exit whenever it became necessary to reduce the facility pressure ratio required for flow simulation. When the capacity of the facility did not require the use of the jet diffuser, the supersonic nozzle exhausted directly into the engine inlet and test chamber.

<u>Facility pressure ratio required for flow simulation</u>. - The facility pressure ratio required to establish flow simulation with and without the jet diffuser for the 28-inch ram-jet engine investigated is presented in figure 8. Two criteria, which were in close agreement, were used to determine the facility pressure ratio at which flow simulation was obtained. As the pressure ratio was increased, the flow was considered established when the shock pattern associated with an overexpanded nozzle passed downstream of the diffuser cowl inlet and an external static pressure on the diffuser cowl lip became constant.

The data of figure 8 show that use of the jet diffuser reduced the facility pressure ratio required to produce the proper flow simulation about 8 percent at a Mach number of 2.35 and about 25 percent at a Mach number of 2.70. Without the jet diffuser, the maximum pressure recovery of the system depends on the nozzle corner-shock strength attainable while maintaining flow simulation. With the jet diffuser, the diffuser action improves the recovery still further. Thus, the jet diffuser provides a rather simple method for increasing the range of Mach numbers over which a given facility can provide proper flow simulation. The data of figure 8 for operation without the jet diffuser are well represented by the equation

$$\text{Facility pressure ratio} = \frac{\left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}}}{2.26}$$

where M is Mach number and γ is ratio of specific heats.

The ratio of test-chamber pressure to nozzle-exit static pressure (in this case, 2.26) is associated with flow separation in the nozzle boundary layer, which affects the flow entering the engine. Other investigations (ref. 5) have found that flow separation in turbulent boundary layer occurs when the ratio of exhaust pressure to nozzle-exit static pressure is about 2. Varying the geometric relations between the nozzle exit and the engine diffuser inlet would influence to some extent the value of this static-pressure ratio at which the boundary-layer separation would affect the flow entering the engine diffuser.

Further verification was given of the occurrence of boundary-layer separation near a pressure ratio of 2 in the Mach number 3.0 facility reported in reference 4. During operation of this facility, a marked flow separation occurred upstream of the nozzle exit in the presence of 3967
a corner shock producing a static-pressure ratio of 2.26.

The data point for the 1.92 Mach number without the jet diffuser was not directly comparable with the other data because it has a mass-flow ratio of only 2.3 as compared to 3.2 for the other supersonic nozzles.

Diffuser subcritical operation and flow simulation. - The degree of subcritical operation possible while maintaining flow simulation is shown in figure 9, by plotting diffuser pressure recovery against the ratio of free-jet static-to-total pressure at the supersonic nozzle exit and diffuser-inlet mass-flow ratio.

The variation of the free-jet nozzle static-to-total pressure ratio from the design value is used as an indication of flow breakdown. The data of figures 9(a) and (b) were obtained with the 1.92 Mach number nozzle with and without the jet diffuser. These data show that without the jet diffuser, the flow simulation remained intact to a subcritical diffuser mass-flow ratio of 0.50 (fig. 9(a)). However, with the jet diffuser installed, the minimum mass-flow ratio for flow simulation was 0.74 (fig. 9(b)). These data, then, indicate that the degree of subcritical operation was considerably reduced when using the jet diffuser.

The data in figure 9(c) were obtained with the 2.35 Mach number nozzle with the jet diffuser and with the 2.50 Mach number nozzle without the jet diffuser. These data indicate the same trends as the data of figures 9(a) and (b), although, as previously indicated, the facility mass-flow ratio is different for the data of figure 9(c).

The criterion of figure 9 implies that the engine-inlet flow is satisfactory until the nozzle wall pressures are affected. However, it is possible that the engine-inlet flow may be influenced by the nozzle corner shock or jet boundary, if either of these intercept the boundary of the subsonic-flow region near the engine cowl. In this case, the limit of adequate simulation might be at a higher mass-flow ratio than is indicated in figure 9.

CONCLUDING REMARKS

Some observations of the operating problems during the investigation of a 28-inch ram-jet engine indicated the influence of improper flow simulation on engine operation and, thus, the importance of examining the flow conditions at the exit of the supersonic nozzle when putting a free-jet facility into operation. For example, the initial engine data disclosed that the engine rich blowout limits were in wide disagreement with those obtained during direct-connect testing by the manufacturer in his facility. Installation of a shadowgraph and high-response instrumentation revealed random pressure pulsations in the flow. Removal of these pulsations by placing a fine spherical screen at the bellmouth inlet of the supersonic nozzle increased the engine rich blowout fuel-air ratio about 10 percent and the peak diffuser pressure recovery 2 points. The flow pulsations had no discernible effect on the supercritical mass-flow ratio or the engine combustion efficiency.

Positioning a jet diffuser at the exit of the supersonic nozzles reduced the facility pressure ratio required for proper flow simulation by 8 to 25 percent as the Mach number was increased from 2.35 to 2.70. However, the jet diffuser sizably decreased the amount of subcritical operation that could be obtained under simulated flow conditions.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, October 8, 1956

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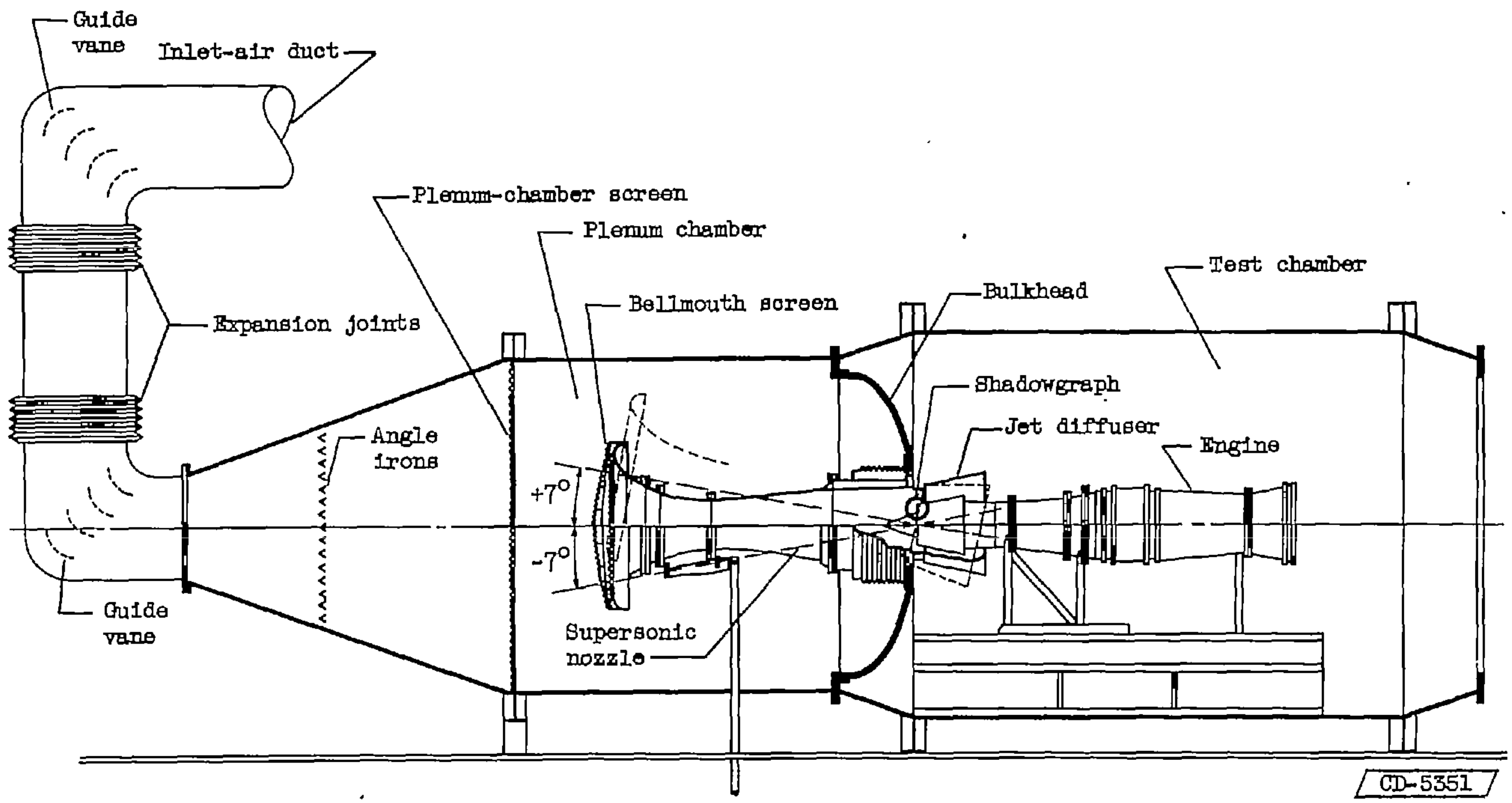

Figure 1. - Schematic diagram of free-jet installation.

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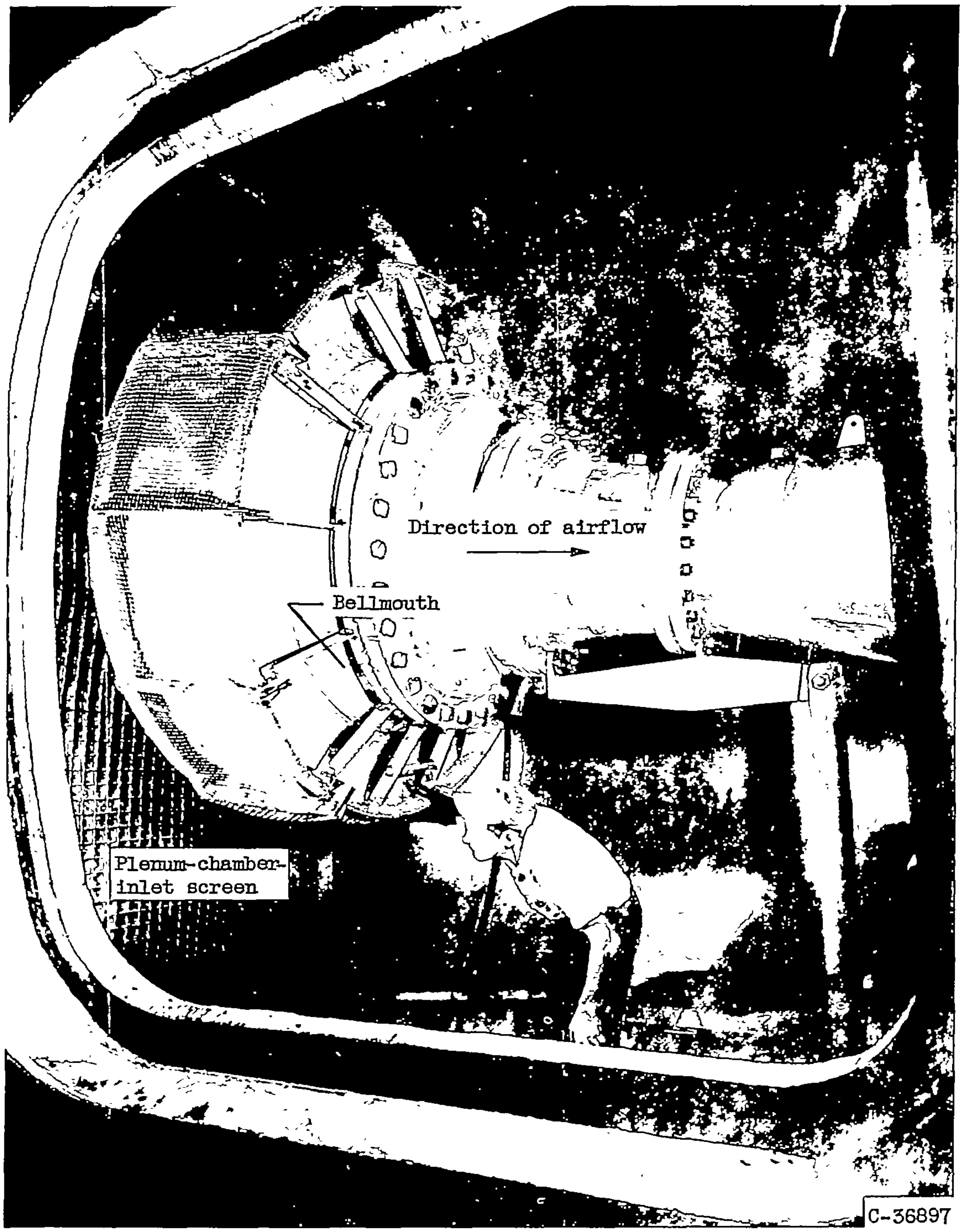

Figure 2. - View of plemum-chamber and bellmouth screens.

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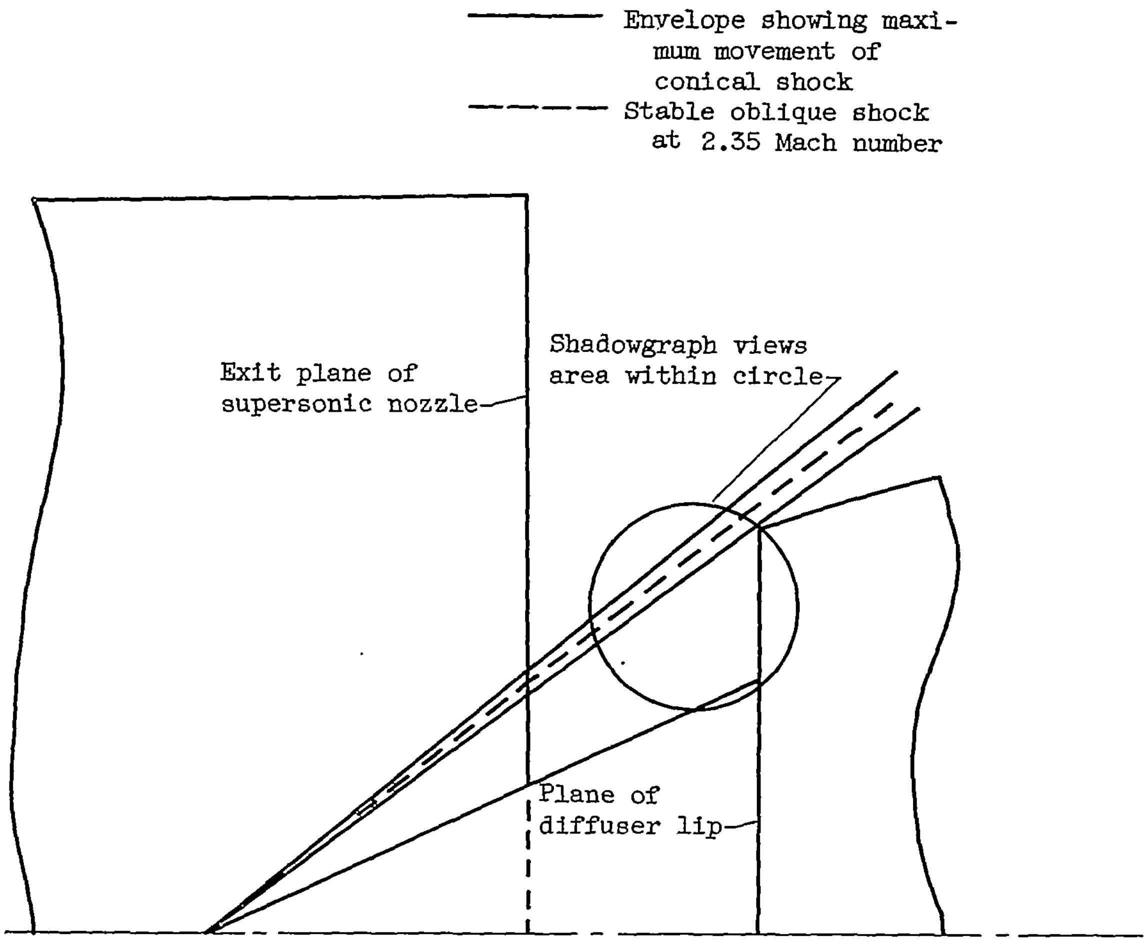

Figure 3. - Schematic diagram showing viewing area of sha

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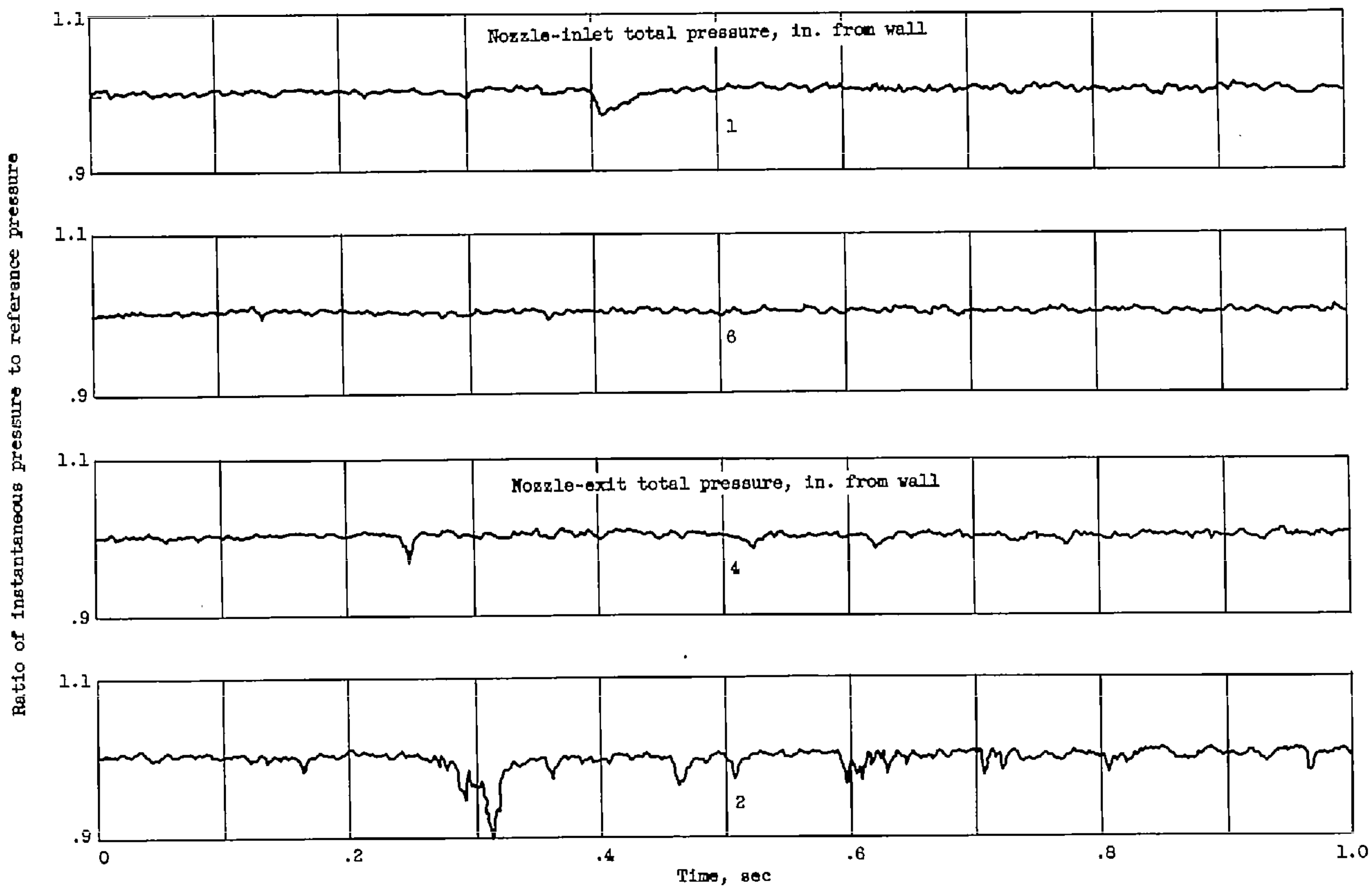

Figure 4. - High-response total-pressure measurements obtained during flow pulsations.

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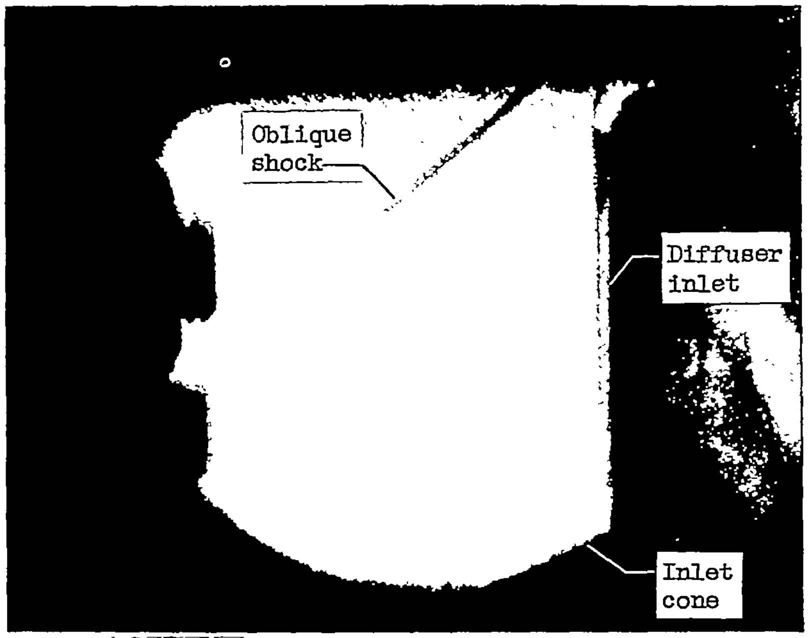
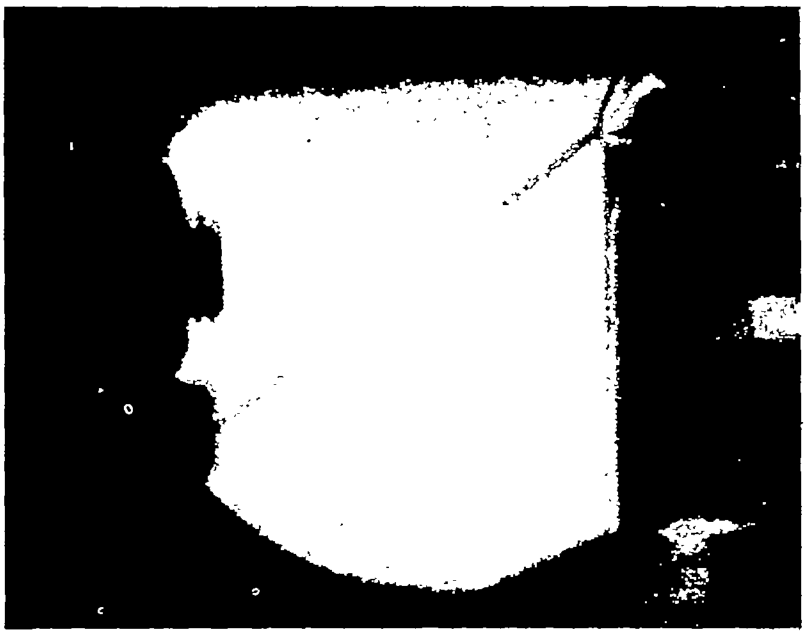


(a) Shock angle, 39.8°.



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(b) Shock angle, 37.0°.

Figure 5. - High-speed movie frames showing limits of conical-shock movement.

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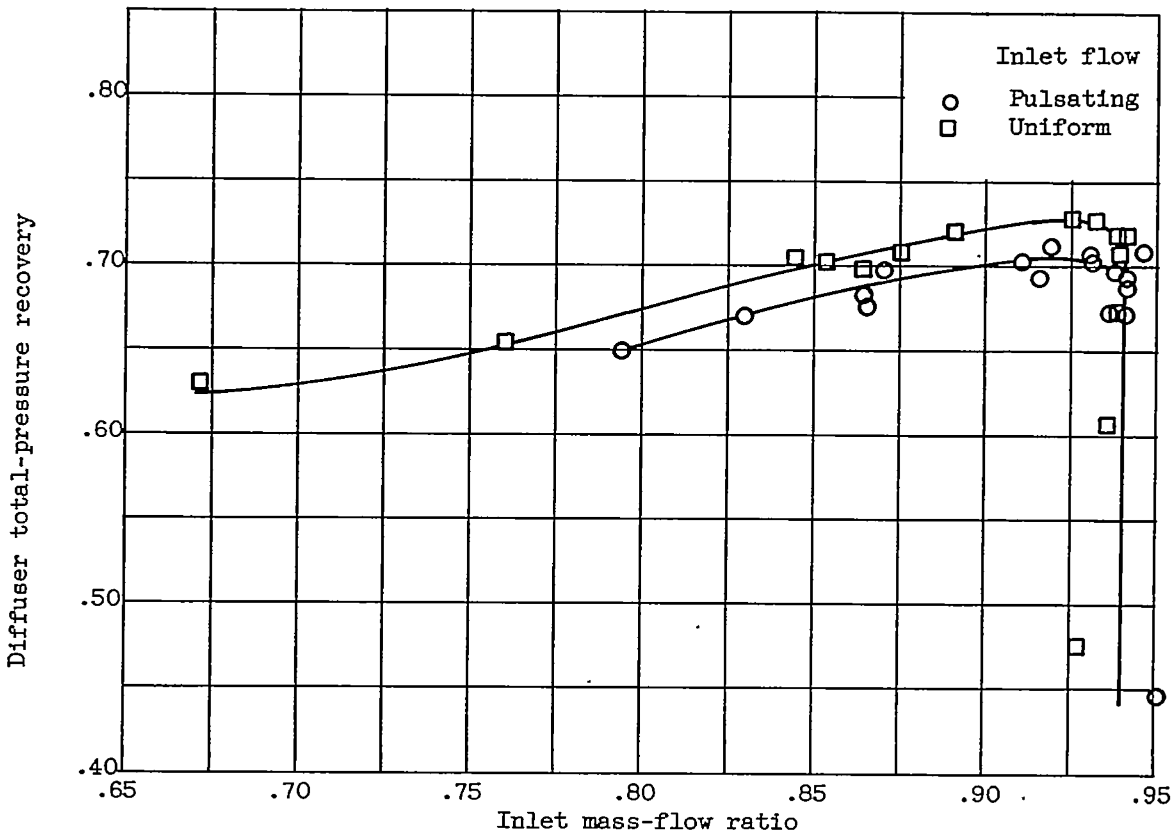


Figure 6. - Effect of flow pulsations on cold-flow diffuser performance. Flight Mach number, 2.35; angle of attack, 0°.

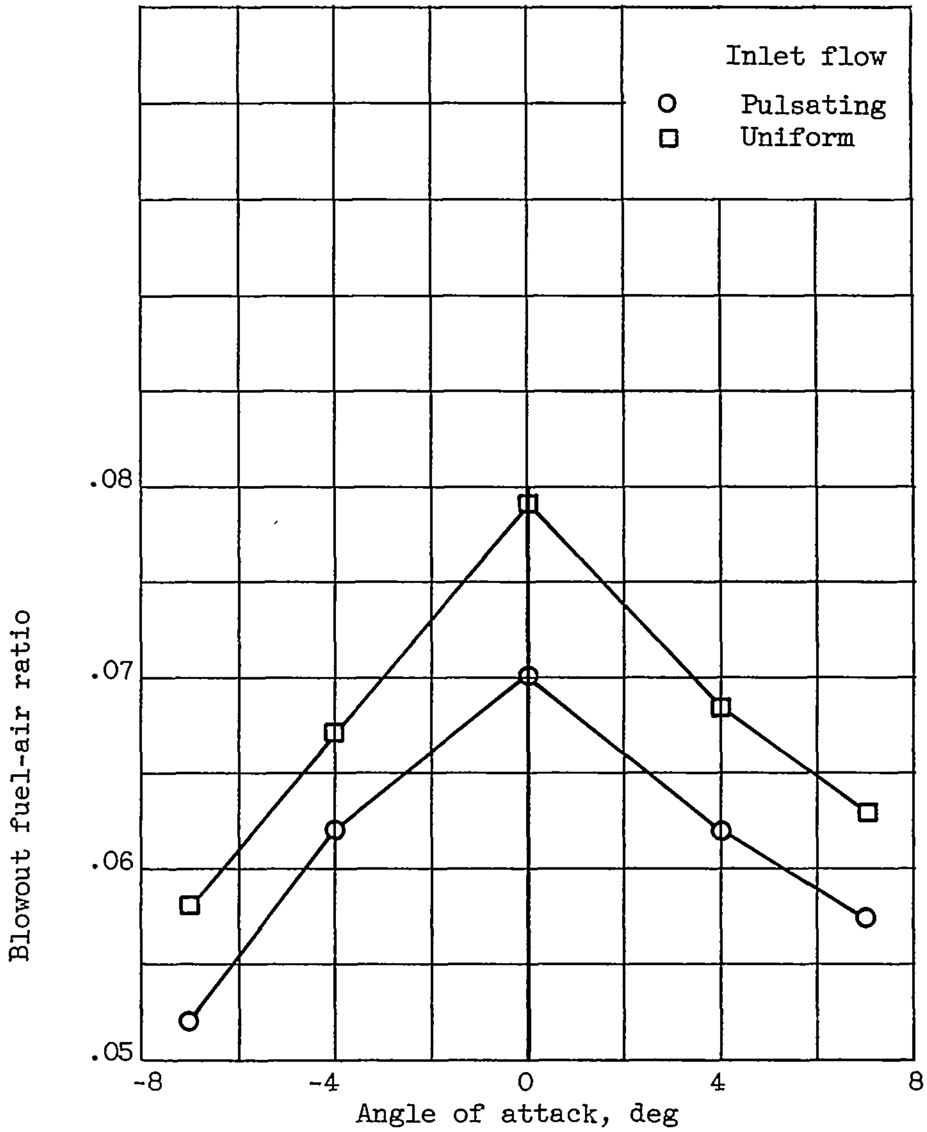


Figure 7. - Effect of flow pulsations on engine rich blowout fuel-air ratio.

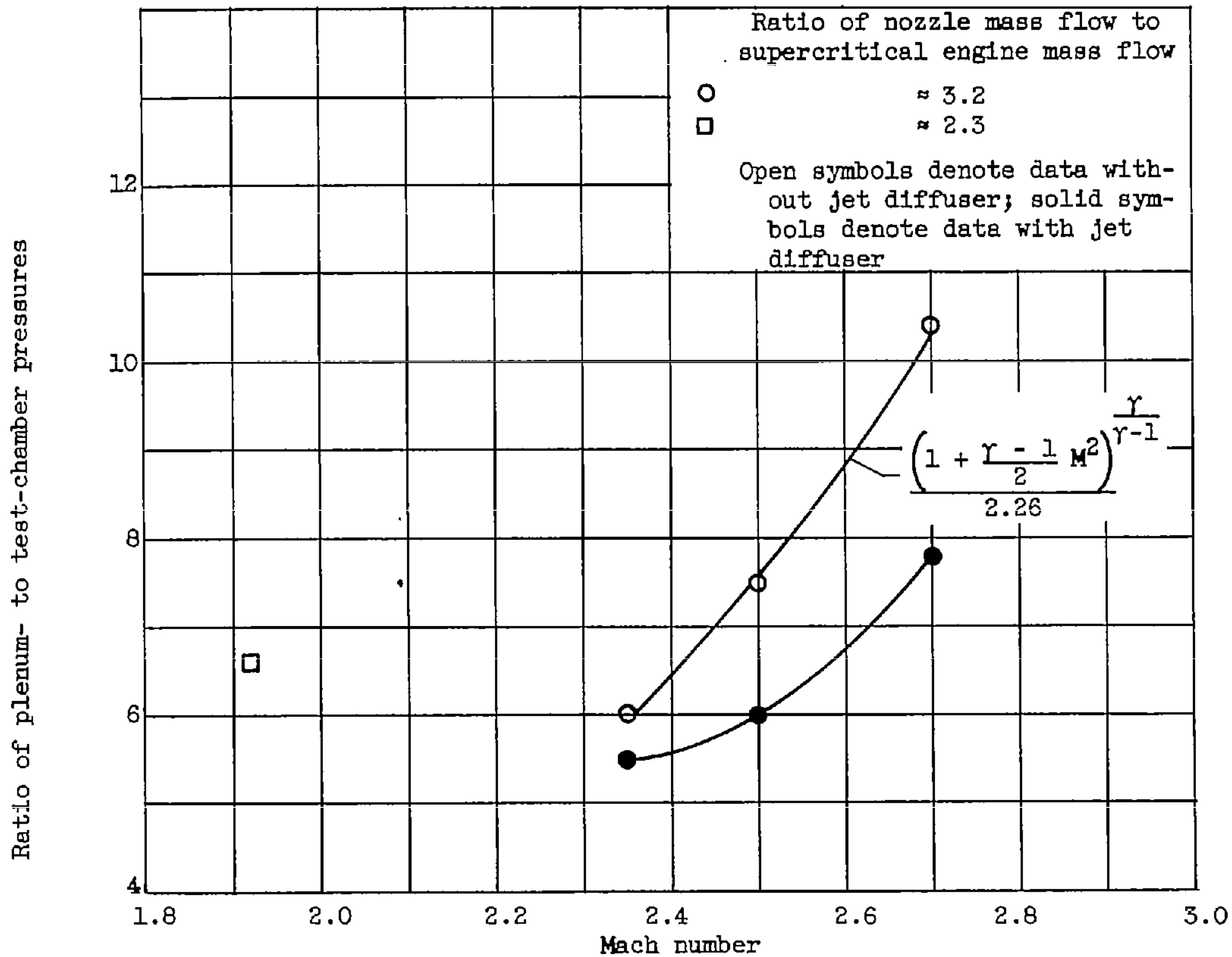
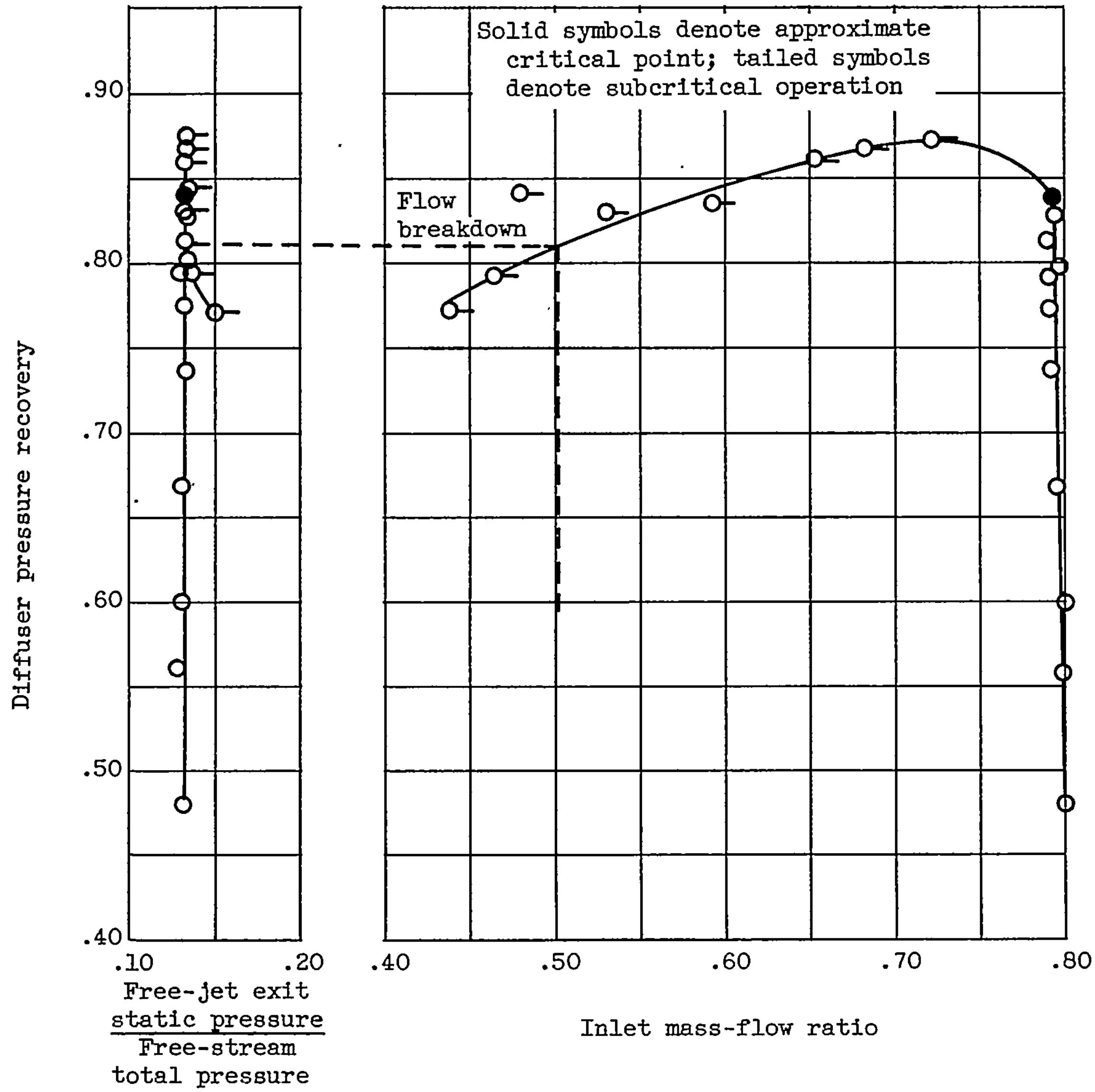
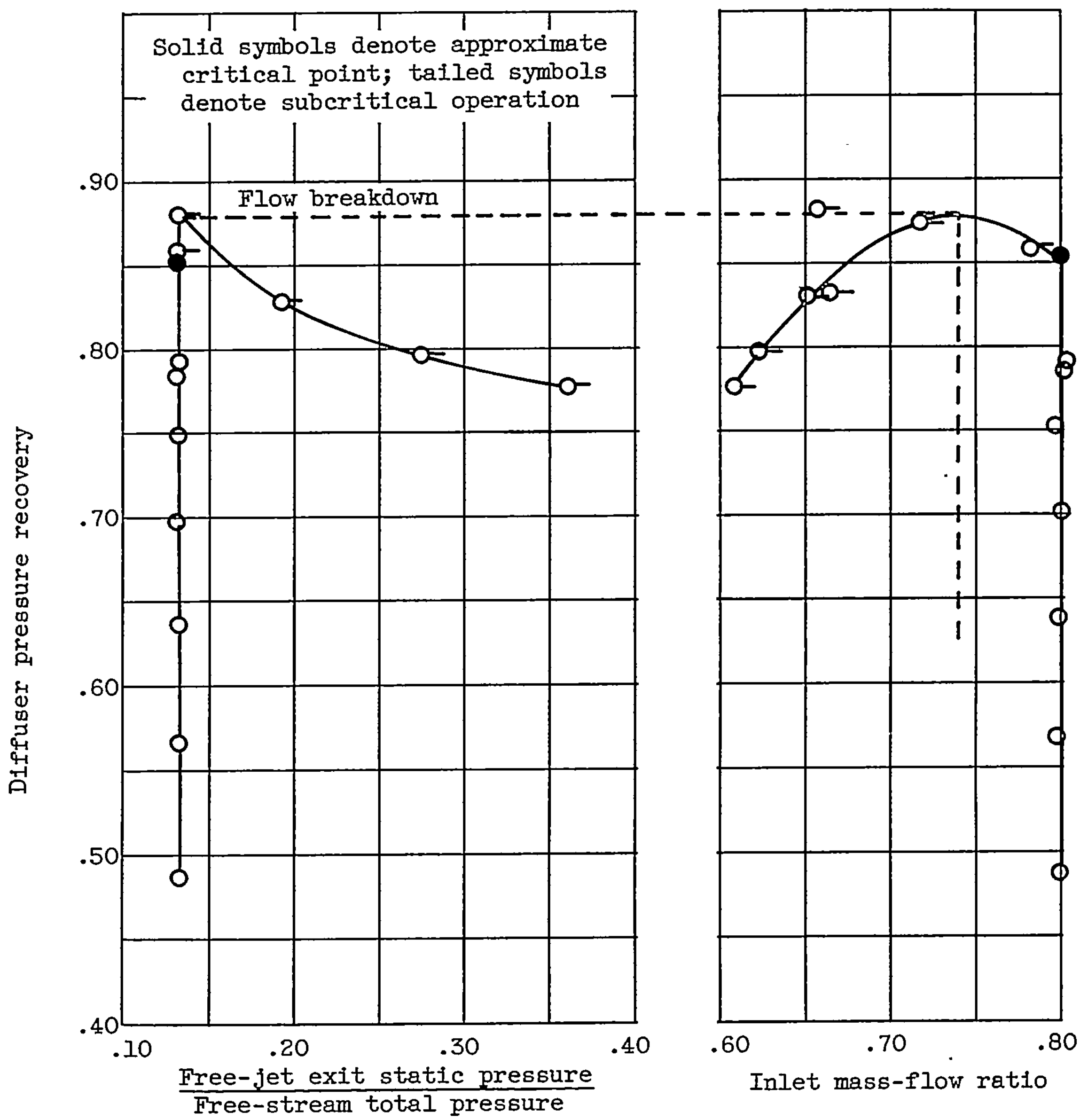


Figure 8. - Facility pressure ratio required to establish and maintain flow simulation at various Mach numbers. M is Mach number and γ is ratio of specific heats.



(a) No jet diffuser; 1.92 Mach number nozzle.

Figure 9. - Effect of subcritical operation on flow simulation. Angle of attack, 0°.



(b) With jet diffuser; 1.92 Mach number nozzle.

Figure 9. - Continued. Effect of subcritical operation on flow simulation. Angle of attack, 0°.

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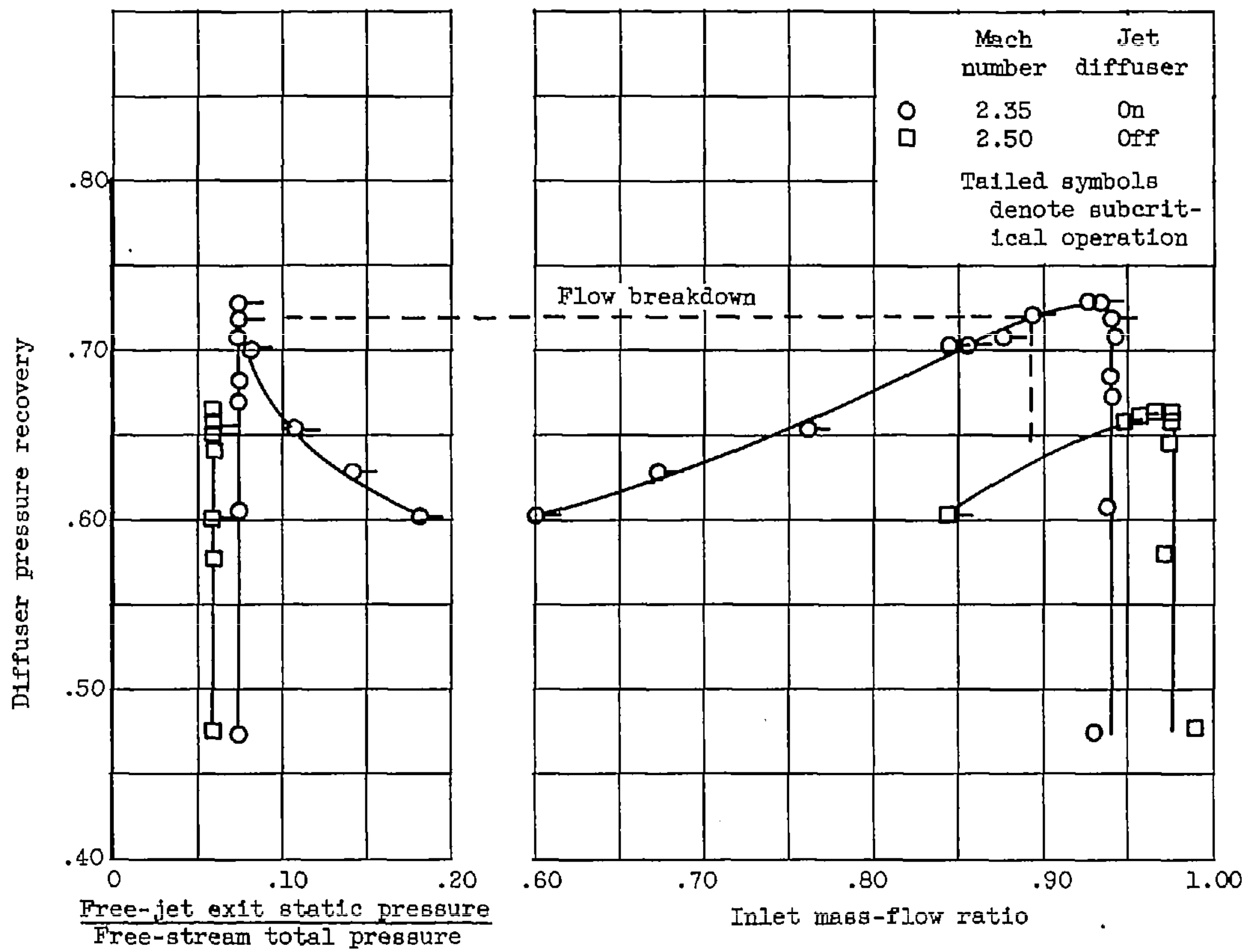

(c) With and without jet diffuser; 2.35 and 2.50 Mach number nozzles.

Figure 9. - Concluded. Effect of subcritical operation on flow simulation. Angle of attack, 0°.

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